

Habitat Suitability Modelling for the Krüper's Nuthatch (*Sitta krueperi*) in the Kaz Mountains and Surrounding Area

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Abstract: Biodiversity loss, habitat fragmentation and climate change are among the primary environmental pressures affecting species distributions. The fact that species dependent on specific habitat conditions are particularly sensitive to environmental changes makes the identification of potential habitats crucial from a conservation biology perspective. In this study, the potential habitat suitability and distribution patterns of the Krüper's nuthatch (*Sitta krueperi*), a bird species live to the Eastern Mediterranean region, were modelled using the MaxEnt (Maximum Entropy) method in the Kaz Mountains and surrounding areas. Thirty sightings of the species obtained during field surveys, along with bioclimatic, topographic and remote sensing-based environmental variables, were incorporated into the model. The multiple relationships between environmental variables were assessed using Pearson correlation analysis, and variables showing high correlation were excluded from the analysis. In model calibration, 70% of the data was used for training and 30% for testing, with analyses conducted in 10 replicates. The model performance was found to be high, with AUC values of 0.947 and 0.927 calculated for the training and test data, respectively. Jackknife analyses indicated that the August NDVI, March NDVI, annual mean temperature (BIO1), Topographic Position Index (TPI) and Topographic Wetness Index (TWI/CTI) variables had the strongest influence on species distribution. Response curves revealed that habitat suitability increases in areas with high vegetation cover density, whilst it decreases under conditions of rising temperature and high humidity. Habitat suitability maps indicated that the most suitable areas for the species are concentrated in coniferous forest ecosystems at medium elevations. The results obtained demonstrate that the distribution of *S. krueperi* is largely shaped by vegetation structure, topographic features and climatic conditions, thereby providing a scientific basis for planning and management efforts aimed at the species' conservation.

Keywords: *Sitta krueperi*, MaxEnt, habitat suitability, species distribution modelling, NDVI, Kaz Mountains.

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1. Introduction

Biodiversity loss, habitat fragmentation and global climate change are among the most significant environmental pressures affecting species distribution today. Species that are particularly dependent on specific habitats tend to be more sensitive to environmental changes, and their ranges may undergo significant contraction. Consequently, determining the current and potential distribution ranges of species has become a fundamental research topic in conservation biology (Guisan & Thuiller, 2005; Elith & Leathwick, 2009).

Species distribution models (SDMs) are powerful tools that estimate habitat suitability by utilising the relationships between species records and environmental variables. In particular, the Maximum Entropy (MaxEnt) algorithm, developed by Phillips et al. (2006), has become one of the most widely used modelling methods over the past twenty years due to its ability to work with presence data alone and its high predictive success (Phillips et al., 2006). Subsequently, Elith et al. (2011) provided a detailed explanation of the ecological interpretability of the MaxEnt model and demonstrated that the method can produce reliable results across different groups of organisms (Elith et al., 2011).

The Krüper's nuthatch (*Sitta krueperi* Pelzeln, 1863) is a bird species belonging to the Sittidae family, with a distribution restricted to the Eastern Mediterranean region. The species' distribution is primarily limited to the Anatolian Peninsula, the island of Lesbos (Lesvos) and the Western Caucasus (Harrap & Quinn, 1996). The Krüper's nuthatch is predominantly associated with coniferous forests, inhabiting in particular forests of Turkish red pine (*Pinus brutia*), black pine (*Pinus nigra*), Taurus fir (*Abies cilicica*) and cedar (*Cedrus libani*) (Harrap & Quinn, 1996; Albayrak & Erdoğan, 2018). Throughout its life cycle, the species' nesting, foraging and sheltering activities are largely dependent on mature forest structure (Albayrak & Erdoğan, 2005b).

The first detailed ecological studies on the Krüper's nuthatch have focused on the species' behavioural characteristics and reproductive biology. In their research conducted Albayrak and Erdoğan (2005a,2005b) examined the species' nesting behaviour, parental care and habitat use, demonstrating that the species prefers mature coniferous forests. In subsequent studies, the same researchers assessed the relationships between the species' habitat preferences and environmental variables, revealing that

altitude, slope aspect, tree species composition and forest structure influence its distribution (Albayrak et al., 2010).

Albayrak et al. (2011) developed one of the first habitat suitability models for the Krüper's nuthatch and demonstrated that the species' distribution is closely linked to elevation, topography and forest cover in particular. The researchers noted that habitat suitability analyses provide important information for the conservation of the species and serve as an effective tool for identifying potential habitats.

One of the most comprehensive studies on the species' current distribution and population density was conducted by Albayrak and Erdoğan (2018). The researchers examined the species' distribution across Turkey and the island of Lesbos, demonstrating that Western Anatolia and the Taurus Mountains are key centres of high density. It was also noted that areas exhibiting high density are largely associated with well-preserved coniferous forests.

The evolutionary history and historical distribution dynamics of the Krüper's nuthatch have also been investigated in recent years. Albayrak et al. (2012) examined the species' phylogeographic structure using mitochondrial DNA and microsatellite data, revealing distinct genetic differentiation among Anatolian populations. Subsequently, Perktaş et al. (2015) reconstructed the species' past distribution using ecological niche models and coalescent-based demographic analyses. They showed that Krüper's nuthatch survived the Last Glacial Maximum largely along the coastal belt of Anatolia, whereas during the Last Interglacial it persisted in southern Anatolia rather than along the coast. These findings support a "refugium within refugium" scenario, in which climate-driven range shifts occurred within Anatolia itself.

However, a review of the current literature reveals that the use of seasonal remote sensing variables to explain the habitat suitability of the Krüper's nuthatch is quite limited. In particular, there are no studies examining the effect of NDVI data from different periods on the species' distribution. NDVI is an important remote sensing indicator representing vegetation density and primary productivity, and is widely used in the assessment of habitat quality (Pettorelli et al., 2005). Therefore, the use of NDVI variables in conjunction with topographic and bioclimatic variables has the potential to explain the species' habitat preferences in greater detail.

The aim of this study is to model habitat suitability for *Sitta krueperi* using the MaxEnt approach and to identify the environmental factors determining the species' distribution. In this context, NDVI layers for March, May and August were evaluated in conjunction with elevation (DEM), topographic position index (TPI), topographic wetness index (TWI/CTI), solar radiation and bioclimatic variables. The aim was to

identify the species' habitat preferences and potential suitable habitats, thereby providing scientific data for future conservation and management efforts.

2. Material and Method

2.1. Study Area

This study was conducted in the Kaz Mountains (Mount Ida) and their immediate surroundings, located in the southern part of the Biga Peninsula in north-western Anatolia. The Kaz Mountains form a natural boundary between the provinces of Çanakkale and Balıkesir and lie within an important transitional zone between the Marmara and Aegean regions (Uysal, 2010). The study area is situated between approximately 39°42'N–26°51'E and reaches an elevation of 1,774 m above sea level. The pronounced elevation gradient in the region leads to significant variations in temperature, humidity and vegetation over short distances (Uysal, 2010; Efe et al., 2015).

The Kaz Mountains possess high habitat diversity due to their location at the intersection of the Mediterranean and Euro-Siberian phytogeographic regions. This transitional character facilitates the coexistence of different plant communities and enhances the region's biological diversity (Uysal, 2010). There are three main vegetation types in the region: forest, scrub and high-mountain vegetation. Within the forest ecosystems, the species present include the Turkish red pine (*Pinus brutia*), black pine (*Pinus nigra*), oriental beech (*Fagus orientalis*) and the Kaz Dağı fir (*Abies nordmanniana* subsp. *equi-trojani*), which is endemic to this region (Uysal, 2010; Efe et al., 2015). Hosting approximately 800 plant taxa, the Kaz Mountains are recognised as one of Turkey's most important areas in terms of flora and, due to their high endemism rate, constitute a significant centre of biological diversity at both national and international levels (Uysal, 2010; Öztürk et al., 2011).

Due to its extensive coniferous and mixed forest areas, topographic heterogeneity and varying microclimatic conditions, the study area provides suitable breeding, foraging and roosting habitats for the *Sitta krueperi*. For this reason, the Kaz Mountains and their surroundings were selected as the study area to model the species' habitat preferences and potential distribution.

2.2. Species Occurrence Data

We obtained presence records for Krüper's Nuthatch (*Sitta krueperi*) during fieldwork conducted in the study area. The sightings of the species were visually observed using binoculars and through a digital camera with telephoto lens, while coordinates of every observation point were taken with the help of Global Position System (GPS) device. In total, 30 independent species records were obtained through

the fieldwork and thus treated as a presence-only data point. Species names were checked against morphological descriptions in the literature and corroborated by photographic records. Coordinate data acquired were imported to a GIS environment and standardized for species distribution modelling.



Figure 1. *Sitta krueperi*

2.3. Environmental Data Preparation

Climatic, topographic and vegetation-related variables were prepared to represent environmental factors that could influence the potential distribution of the species. Climate data were obtained from the WorldClim v2.1 database at a spatial resolution of approximately 1 km, and bioclimatic variables defining temperature and precipitation regimes were incorporated into the model (Fick & Hijmans, 2017; Booth, 2022).

Topographic variables were generated using the ASTER GDEM Version 3 digital elevation model. Elevation, slope and aspect layers were created from the elevation model, and various topographic indices representing different aspects of the terrain were calculated (Abrams et al., 2020; Gesch et al., 2016; Amatulli et al., 2018; Uuemaa et al., 2020). In this context, the Topographic Position Index (TPI), Ruggedness Index (RI), Roughness Index (RO), Topographic Wetness Index (TWI), Shading Index (SHI) and Solar Illumination Index (SII) variables were obtained. The RI and RO variables, which represent terrain ruggedness and surface heterogeneity, were used to determine the topographic complexity within the study area (Amatulli et al., 2018; Trevisani et al., 2023). Whilst the TWI reflects potential moisture accumulation, the SHI and SII were calculated to reveal the effects of topography on solar radiation conditions (Winzeler et al., 2022; Altunel, 2023; Ďuračiová & Pružinec, 2022).

The Temperature Index (TI), proposed by McCune and Keon (2002), was used to represent temperature differences on the land surface. This index, derived by jointly evaluating slope and aspect information, expresses the potential heat load. High index values indicate microhabitats that receive more solar energy and are relatively warmer, whilst low values indicate cooler areas.

NDVI data obtained from the MODIS MOD13Q1 product were used to represent vegetation characteristics (Huang et al. 2021). A layer illustrating long-term vegetation productivity was prepared by averaging monthly composites derived from imagery spanning the years 2017–2022. Thus, vegetation productivity and habitat quality within the study area were spatially represented.

2.4. Multicollinearity Analysis

A Pearson correlation analysis was performed prior to modelling to identify multicollinearity among the environmental variables. Upon examination of the correlation matrix, it was observed that there were high levels of positive or negative relationships between certain pairs of bioclimatic variables (Figure 2). In particular, strong correlations were identified between different derivatives of temperature and precipitation variables; as this could result in the same environmental information being included in the model more than once, these were excluded from the analysis. From the variable pairs where the absolute value of the correlation coefficient $|r|$ was ≥ 0.70 , those variables that were ecologically more meaningful or interpretable were retained, whilst the others were excluded from the analysis. As a result of this screening process, the set of variables to be used in the model was established, and potential multicollinearity effects between variables were reduced (Figure 2).

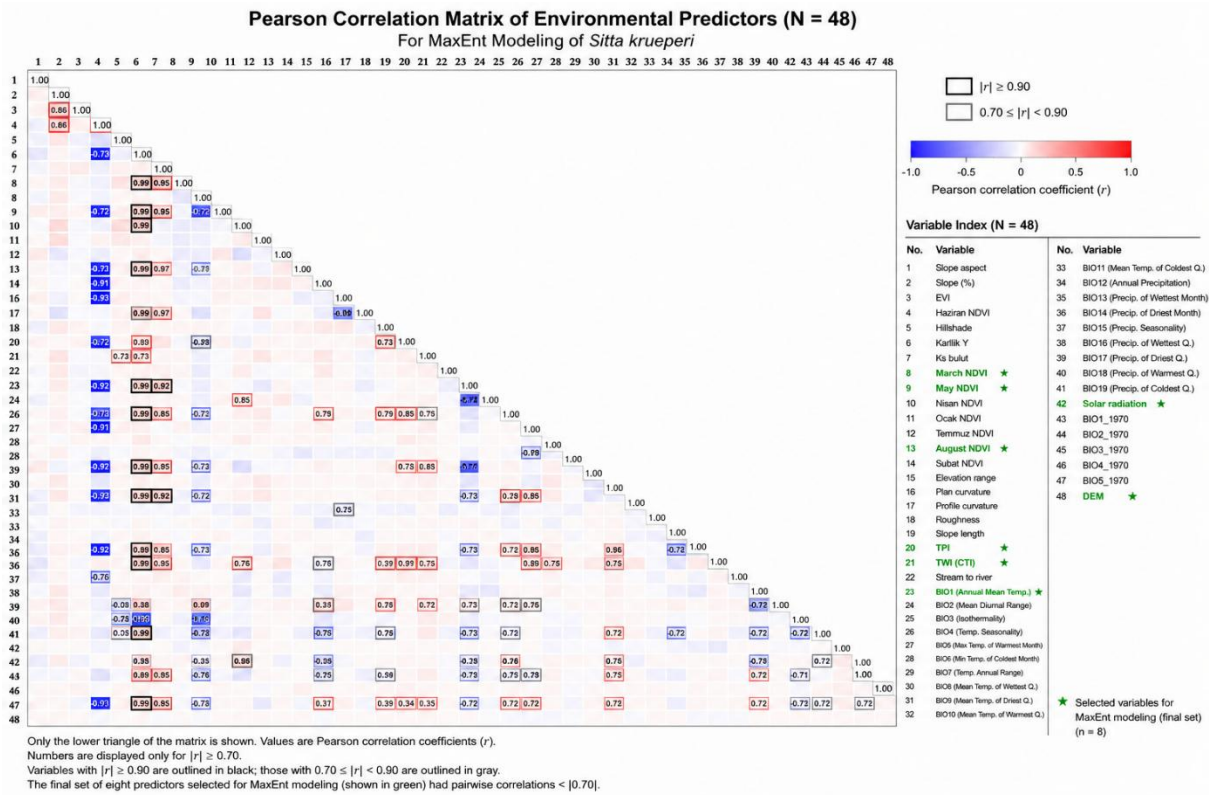


Figure 2. Pearson correlation matrix of 48 environmental variables considered for MaxEnt modelling of *Sitta krueperi*. Predictor variables selected for the final model are highlighted in green. Correlation coefficients with $|r| \geq 0.70$ are shown; grey and black boxes indicate moderate (0.70–0.89) and strong (≥ 0.90) collinearity, respectively. Blue and red colours represent negative and positive correlations.

2.5. Species Distribution Modelling

The MaxEnt 3.4.4 software, based on the Maximum Entropy algorithm, was used to determine the potential distribution areas of the Krüper's Nuthatch. The species' habitat suitability was modelled by combining species occurrence records with environmental variable layers.

For model calibration, 70% of the records were randomly allocated as training data and 30% as test data. To enhance the reliability of the predictions, analyses were conducted in 10 replicates, and the results of each replicate were averaged to obtain the final habitat suitability model. The complementary cloglog format was selected as the output format, thereby generating probability values representing habitat suitability for each pixel.

Model performance was evaluated using the Area Under the Receiver Operating Characteristic Curve (AUC) value. Furthermore, the contributions of environmental variables to the model were determined by examining error rates, response curves and Jackknife analyses. Variable importance was assessed

using permutation contributions and Jackknife tests, and the environmental factors most influencing species distribution were identified. In MaxEnt and other species distribution models, AUC is used as a common performance metric—ranging from 0 to 1 and independent of the threshold—that indicates the model's ability to distinguish between suitable and unsuitable areas (Phillips et al. 2006). Response curves are interpreted in many MaxEnt studies to reveal how habitat suitability varies across each environmental variable and to identify the species' preference ranges (Smith & Santos 2020). Jackknife tests were used to determine variable importance; this allowed the environmental factors most influencing species distribution to be identified. In MaxEnt, the Jackknife method determines the relative importance of variables by calculating the change in model performance when each variable is removed individually or used in isolation (Naqibzadeh et al., 2021).

As a result of the analysis, species distribution maps showing habitat suitability values for the study area were produced, and potential suitable habitats were visualised within a geographic information system (GIS) environment. The maps obtained were used to determine the current and potential distribution areas of *S. krueperi*.

3. Results

The MaxEnt model developed for *Sitta krueperi* has demonstrated high discriminatory performance. In the ROC analysis, the AUC value was calculated as 0.947 for the training data and 0.927 for the test data (Figure 3). The fact that both values are well above the level of random guessing indicates that the model strongly distinguishes between suitable and unsuitable habitats for the species. The small difference between the training and test AUC values indicates that the model does not overfit and produces consistent predictions on independent test data. The AUC value is widely used to assess the discriminatory power of species distribution models.

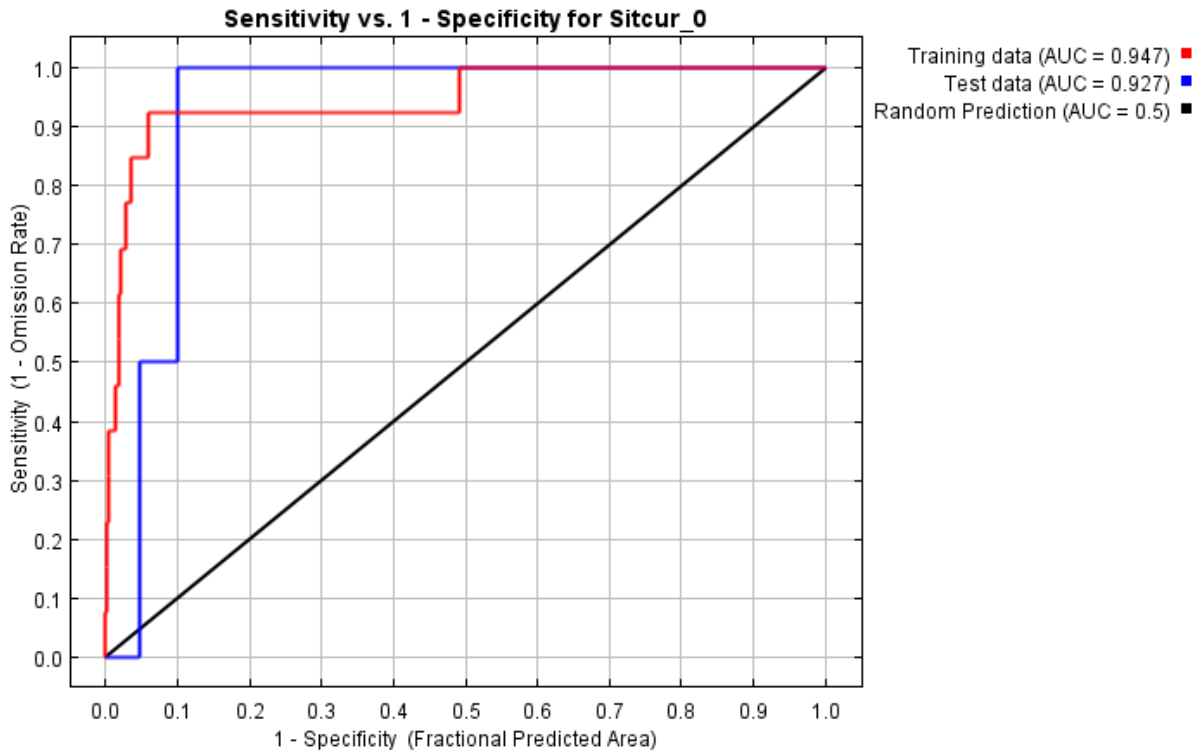


Figure 3. Receiver operating characteristic (ROC) curve of the MaxEnt model developed for *Sitta krueperi*. The model exhibited high predictive performance with training and test AUC values of 0.947 and 0.927, respectively, indicating a strong ability to discriminate suitable from unsuitable habitats. The diagonal black line represents random prediction (AUC = 0.5).

According to the Jackknife analysis, the variables *august_ndvi*, *march_ndvi*, *bio_1*, *tpi* and *twi_cti* contributed most significantly to model performance. In particular, the fact that the *august_ndvi* and *march_ndvi* variables alone produced high AUC values indicates that vegetation density and seasonal plant productivity are important in explaining species distribution. The *bio_1* variable has shown that the temperature regime is one of the key environmental factors limiting the species' potential distribution. The *tpi* and *twi_cti* variables, meanwhile, have revealed that topographic location and moisture conditions are decisive factors in habitat suitability. The solar variable's contribution to model performance on its own remained low (Figure 4).

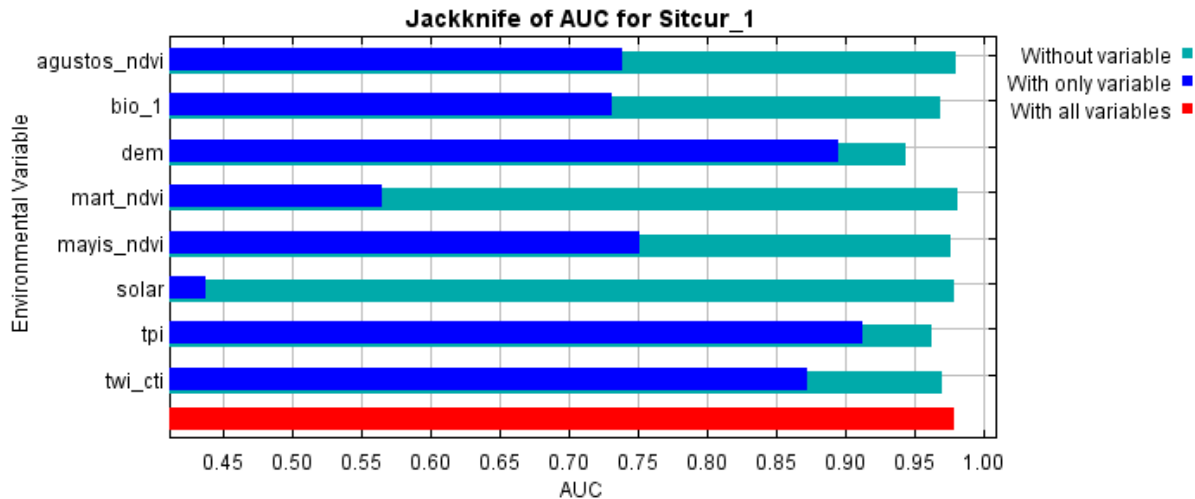


Figure 4. Jackknife analysis of environmental variable importance in the MaxEnt model for *Sitta krueperi*. Bars indicate model gain obtained when each variable was used in isolation (blue) and when omitted from the full model (turquoise), compared with the gain achieved using all variables (red). NDVI-related variables, annual mean temperature (BIO1), topographic position index (TPI), and topographic wetness index (TWI/CTI) contributed most strongly to model performance.

The response curve results indicate that habitat suitability for *S. krueperi* increases with higher NDVI values. Suitability values rose in tandem with increasing NDVI in the August, March and May NDVI curves, suggesting that the species is associated with forested areas possessing high vegetation cover. The bio_1 curve showed that habitat suitability decreased as the annual average temperature increased; this result suggests that the species is inclined towards cooler climatic conditions. The DEM curve showed that suitability reached a maximum in the mid-elevation zone and declined rapidly at very high elevations. The TPI variable produced the highest suitability values in areas of moderate topographic position, whilst the TWI/CTI curve indicated that suitability decreased in areas with high humidity/water accumulation potential. In the solar radiation curve, habitat suitability decreased as radiation increased (Figure 5).

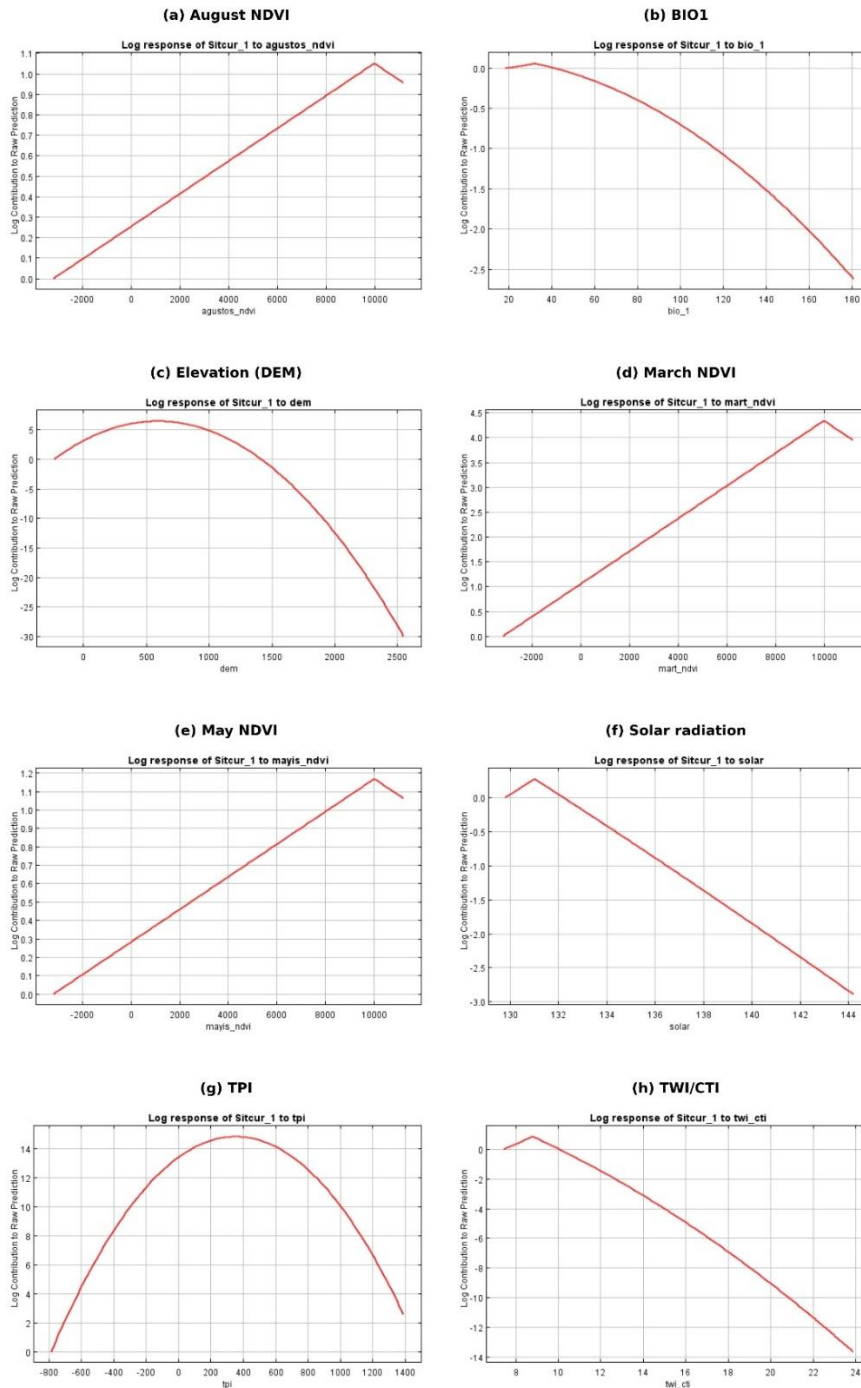


Figure 5. Response curves showing the effects of environmental predictors on habitat suitability of *Sitta krueperi* generated by the MaxEnt model: (a) August NDVI, (b) annual mean temperature (BIO1), (c) elevation (DEM), (d) March NDVI, (e) May NDVI, (f) solar radiation, (g) topographic position index (TPI), and (h) topographic wetness index/compound topographic index (TWI/CTI). Positive responses to NDVI variables indicate an association with dense and productive forest vegetation, whereas suitability decreases with increasing raw annual mean temperature, solar radiation, and excessive moisture conditions.

On the habitat suitability map, areas of high suitability are shown in shades of red and orange, whilst areas of low suitability are shown in shades of blue. The map indicates that high suitability areas for the species are fragmented but clearly concentrated in mountainous and forested belts. In particular, areas with a combination of high NDVI, moderate elevation, low–moderate temperature and suitable topographic location were associated with higher habitat suitability by the model. In contrast, areas of low suitability appear to be associated with low vegetation density, high solar radiation, or unsuitable topographic/moisture conditions. These results indicate that the potential distribution of *S. krueperi* is shaped by the combined influence of climatic, vegetation, and topographic variables (Figure 6).

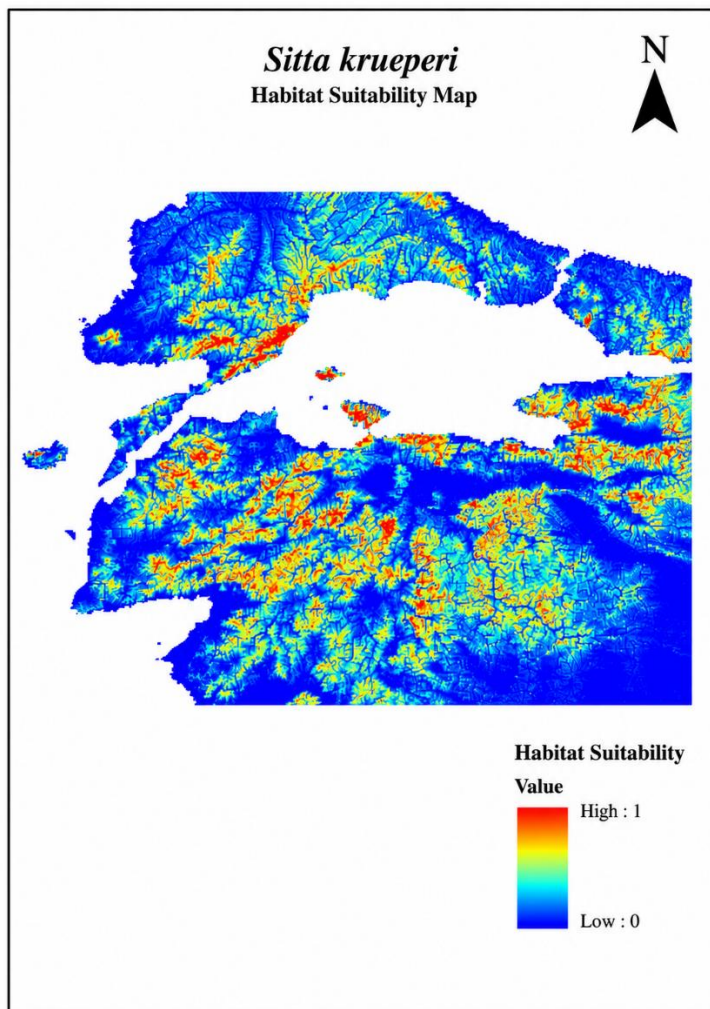


Figure 6. Predicted habitat suitability map for *Sitta krueperi* derived from the MaxEnt model. Habitat suitability values range from 0 (low suitability, blue) to 1 (high suitability, red). Areas with high suitability are primarily concentrated in mountainous and forested regions characterized by favorable vegetation cover, intermediate elevations, and suitable topographic conditions.

4. Discussion and Conclusion

The MaxEnt model developed in this study demonstrated high predictive performance for *Sitta krueperi* (AUC_{train} = 0.947; AUC_{test} = 0.927). The concentration of areas showing high suitability on the habitat suitability map, particularly within mountainous forest belts, is consistent with the species' known ecological requirements. The distribution pattern obtained is consistent with previous studies indicating that the Krüper's nuthatch is dependent on coniferous forest ecosystems in Anatolia (Albayrak & Erdoğan, 2005b; Albayrak & Erdoğan, 2018).

The fact that the August NDVI, May NDVI and March NDVI variables contributed most significantly to model performance in the Jackknife analysis indicates that habitat suitability is directly related to vegetation density and seasonal productivity. NDVI is used as a spatial indicator of vegetation productivity and a continuous determinant of habitat characteristics (dominant cover type, productivity, heterogeneity); it has been shown to have strong correlations with biological responses such as bird diversity and species richness (Bonthoux et al. 2018; Hobi et al. 2017; Radeloff et al. 2019). A large part of the species' life cycle takes place in mature coniferous forests, and its feeding, sheltering and nesting activities are dependent on dense tree cover (Albayrak & Erdoğan, 2005b). Field studies conducted in southern Turkey have reported that the Krüper's nuthatch reaches high densities particularly in black pine (Albayrak et al., 2010). Therefore, the dominant role of NDVI variables in the model is an expected result.

Response curve analyses similarly revealed that habitat suitability increases with higher NDVI values. In particular, the linear increases in the August and March NDVI curves indicate that the species prefers forest habitats with continuous and high biomass throughout the year. This suggests that, although the Krüper's nuthatch is distributed across the Mediterranean basin, it is more associated with closed and mature coniferous forests than with open scrublands.

Model results indicate that the temperature variable (BIO1) limits habitat suitability. The decrease in habitat suitability as the annual average temperature increases suggests that, despite being found in the Mediterranean climate zone, the species prefers cool, high-altitude forests rather than warm lowland areas. Similarly, the dome-shaped response curve obtained for the DEM variable indicates that the species has a specific elevation optimum. The fact that habitat suitability peaks at medium elevations and then declines is consistent with the previously reported dense population distributions within the 1000–1600 m elevation band (Albayrak et al., 2010).

The bell-shaped curve formed by the TPI variable indicates that the species prefers topographically moderately elevated slopes and ridge systems. Conversely, the rapid decline in habitat suitability at high TWI values suggests that the species does not favour excessively humid areas with poor drainage. These results are consistent with the characteristic topographic structure of Mediterranean coniferous forests.

The spatial distribution pattern obtained in this study shows striking similarities with the historical niche model developed by Perктаş et al. (2015). That study revealed that the Krüper's nuthatch persisted along the coastal belt of Anatolia during the Last Glacial Maximum, subsequently expanding towards its current distribution area, particularly starting from southern Anatolia. The researchers noted that the species survived within a refugium in southern Anatolia during the Last Interglacial period and that its current distribution originates from this historical core area.

In our habitat suitability map, the concentration of areas showing high suitability, particularly in the Western Taurus, Central Taurus and specific forest belts of Northern Anatolia, largely coincides with the historical dispersal corridors defined by Perктаş et al. (2015). This indicates that current habitat suitability is a result not only of present-day environmental conditions but also of the species' historical demographic processes and post-glacial dispersal dynamics.

Perктаş et al. (2015) also predicted that under future climate scenarios, the species' distribution range may contract towards the coastal belt. The fact that a significant proportion of the variables determining habitat suitability in our study are related to temperature and vegetation dynamics supports this prediction. In particular, given the decrease in habitat suitability with rising temperatures and the species' dependence on dense forest cover, it is thought that the aridification and changes in forest structure caused by climate change may negatively affect the species' future distribution.

The resulting model indicates that the distribution of *Sitta krueperi* is primarily determined by forest cover density, elevation and topographic conditions. The areas where the species currently exhibits high suitability also overlap with regions that served as refuges during past climatic fluctuations. Therefore, the conservation of mature coniferous forests in Western and Southern Anatolia is of critical importance for the long-term conservation of the species.

Ethics Committee Approval

N/A.

Peer-review

Externally peer-reviewed.

Author Contributions

Conceptualization: A.K.; Investigation: A.K., S.K.; Material and Methodology: A.K.,S.K.; Supervision: A.K.; Visualization: A.K.; Writing-Original Draft: A.K.,S.K.; Writing-review & Editing: A.K.; Other: All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors have no conflicts of interest to declare.

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